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EXPERIMENTAL INVESTIGATION OF AN OSCILLATING FLOW GENERATOR

by

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The device was constructed in the NPS machine shop. It consisted of a flat plate that is mounted on two rail guides such that it can execute a linear back-and-forth motion. The blade oscillation is flow induced due to the lift and the moment generated on the flat plate in such a way that the plate reverses direction at the stroke endpoints without active control. Tests in two water channels and one towing tank showed that flow-induced blade oscillation could be achieved for certain combinations of flow speed, blade size and pitch axis location. It is concluded that additional testing is warranted to further develop and gain understanding of this technology and its possible application to renewable power generation.

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EXPERIMENTAL INVESTIGATION
OF AN OSCILLATING FLOW GENERATOR

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ABSTRACT

The objective of this project was to construct and test a device that can transform fluid flow into the continuous oscillatory linear motion of a hydro/airfoil. This device may be used to generate power from a renewable energy source such as tidal flow or wind power.

The device was constructed in the NPS machine shop. It consisted of a flat plate that was mounted on two rail guides such that it could execute a linear back-and-forth motion. The blade oscillation was flow induced due to the lift and the moment generated on the flat plate in such a way that the plate reversed direction at the stroke endpoints without active control. Tests in two water channels and one towing tank showed that flow-induced blade oscillation could be achieved for certain combinations of flow speed, blade size and pitch axis location. It was concluded that additional testing was warranted to further develop and gain understanding of this technology and its possible application to renewable power generation.

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Finally, I'd like to thank Professor Timothy Stanton and Mr. James Stockel of the NPS Oceanography Department for their help on setting up the digital electromagnetic velocimeter.

I. INTRODUCTION

For many years, flapping wing aerodynamics and hydrodynamics have been of considerable interest to scientists studying the mechanics and dynamics of flying and swimming animals (fish, cetaceans, birds and insects) and the propulsion technologies based on the flapping-wing principle. This special field of aerodynamics received a significant boost when, in 1996, the Defense Research Projects Agency (DARPA) announced a request for proposals to demonstrate the feasibility of micro air vehicles (MAVs). Over the past fifteen years, a number of investigators have explored the use of flapping wing technology on MAVs. Recent reviews of flapping wing aerodynamics have been published by [1] and [2].

It is well known that flapping wings can be used either as thrust generators (propellers) or as power generators (turbines). This can be understood from Figure 1 [1], where an airfoil is shown in a combined pitch and plunge motion. The key parameter for determining whether this airfoil generates thrust or extracts power from the flow is the effective angle of attack. In Figure 1a, the airfoil is oscillating in both pitch and plunge, but with a small pitch amplitude so that the angle of attack (relative to the flight path) is negative. In this case thrust is being generated. On the other hand, in Figure 1c, the airfoil is pitched with a large amplitude, creating a positive angle of attack. In this case, power is extracted from the flow. It is also noteworthy that in both cases, the pitch angle is a maximum when the plunge amplitude is zero, meaning that there is a 90-degree phase angle between the pitch and plunge oscillations. Figure 1b shows the case when the induced angle of attack is just offset by the geometric angle of attack. In this case, the airfoil is said to feather through the flow.

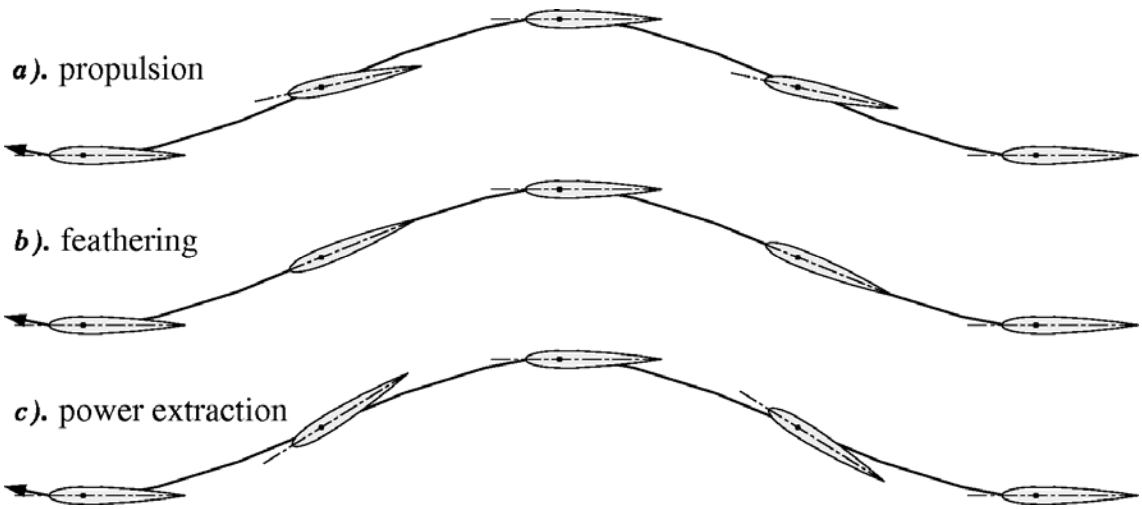

Figure 1. Airfoil pitch and plunge motion.

The case of power extraction is a well-recognized and respected phenomenon in aeronautical engineering. It can lead to explosive flutter and destruction of aircraft wings and tail surfaces in a few seconds. Destructive flutter cases were already encountered during World War I. The understanding and prevention of flutter, therefore, became a firm requirement that led to the development of the field of aircraft aeroelasticity. It also led to the recognition that it might be possible to exploit the flutter phenomenon for power generation. For example, W. J. Duncan [3] described a flutter engine in his introductory survey paper in Volume I of the AGARD Manual of Aeroelasticity.

In contrast to the rapid increase of interest in flapping wing aerodynamics applied to micro aero vehicles for propulsive and lifting purposes, relatively little attention has been paid to the use of flapping wings for power generation purposes. In 1981 McKinney and DeLaurier [4] built and wind tunnel tested a small wind power generator at the University of Toronto. Its operating principle can be readily understood by looking at Figure 2, where it is seen that the motion and the induced forces are in the same direction throughout the whole oscillation cycle if there is a 90-degree phase angle between pitch and plunge (as already pointed out), whereas the lift opposes the motion during parts of the cycle if there is a zero phase angle, as also shown in Figure 2 [1]. In the late 1990s, the British company Engineering Business Limited [5] started the development of a 150 kW oscillating-foil hydropower generator to produce power from a 4-knot tidal stream.

Tests in a Scottish fjord showed that the power generator was capable of producing 90 kW in a 3-knot flow, but further development was stopped due to lack of additional funding by the British government.

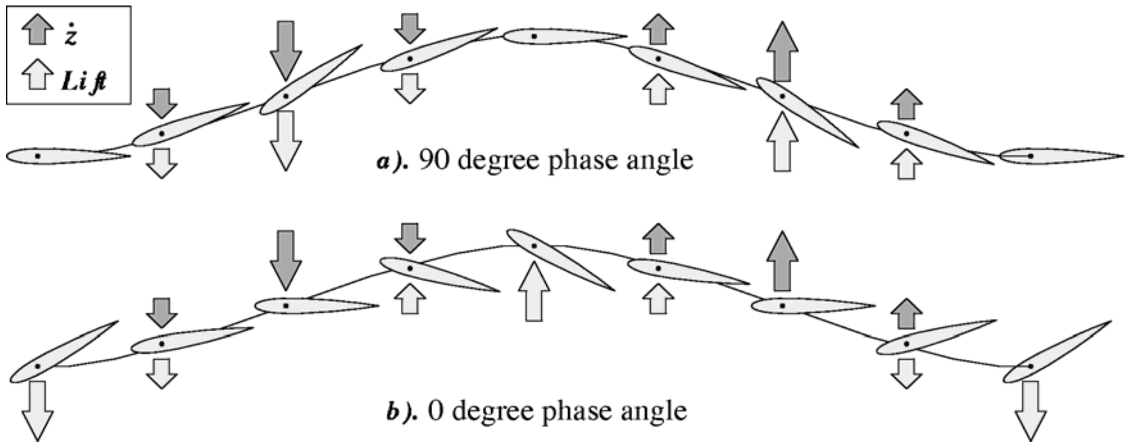

Figure 2. Motion and induced lift of flapping wings for different phase angles.

During the same time period, Platzer and associates developed and tested two micro-power generators [6, 7, 8, 9]. In parallel, they used potential flow and viscous flow (Navier-Stokes) codes [6, 8, 10] to predict the flow through oscillating-flow power generators and to determine the conditions for optimum power output and efficiency. A Navier-Stokes analysis of oscillating-foil power generators was also published by [11] in Canada. Oscillating-foil power generation is also being studied in Japan [12].

The micro-power generators developed by Platzer and associates required a relatively complicated mechanical control system to enforce a 90degree phase angle between the pitch and plunge oscillations. Such systems are likely to lead to operational and maintenance concerns.

These considerations led Platzer and Bradley [13] to the idea of replacing the mechanical control system by a fluid mechanical system such that the foil would be induced into a self-excited oscillation by the fluid flow itself. Further study of this idea also led to the recognition that a flow-induced oscillator would be oscillating in a square-wave type motion rather than a purely sinusoidal motion. The Navier-Stokes computations of [10] confirmed the potential superiority of such an oscillator.

These considerations led to the proposal of developing and demonstrating a new oscillating-flow generator for the purpose of confirming or disproving the feasibility of a flow-induced square-wave type oscillator. Therefore, in the following sections, the specific objective and the test facilities, experimental approaches and test results are described. This is followed by a discussion and summary of the results and recommendations for future work.

II. THE OSCILLATING FLOW MODEL

A. TEST OBJECTIVES

1) Investigate the feasibility of developing a device which can be driven into self-sustained flow-induced linear oscillations.

2) Determine the device parameters and flow conditions which lead to self-sustained oscillations of a flat plate.

3) Visualize the fluid flow and the flat plate oscillations in the two water tunnels and the towing tank of the Mechanical Engineering Hydrodynamics Laboratory.

B. THE MODEL

The purpose of the oscillating flow model, or oscillator, which is shown in Figure 3, is to transform fluid flow into transverse linear motion (power). A device was constructed which, when placed in fluid flow, produces lift via a flat plate. The lift force is transferred to a small block that travels linearly on two rails that run perpendicular to the fluid flow. The block traverses from side to side in response to the lift generated on the blade. The L-shaped moment arm mounted on the top side of the blade is used to initiate motion reversal. The oscillator consists of the following components:

- Aluminum Base: 38.1 cm long by 15.3 cm wide by 2.1 cm thick.
- Small Aluminum Block: 15.2 cm long by 5.0 cm wide by 1.3 cm thick.
- Bearings for Linear Motion (2): Thomson SPB-6 Super Ball Bushing Pillow Block.
- Rails (2) with Mounts (4): Rails are 3/8 inch diameter steel and 38.1 cm long.
- Bearing for Rotation: Ball Bearing with ½ inch inner diameter.
- Shaft: 1/2 inch diameter steel cylindrical shaft. Has a cut through the middle of one end and small holes drilled for the flat plate attachment.

- Flat Plate (2): One short (14.3 cm chord, 18.6 cm span) and one long (14.3cm chord, 30.5 cm span). The blade is made of 1.5 mm thick aluminum. There is a slit that is cut along the upper portion of the plate that allows varying the pitch axis location.
- Moment Arm: 13 cm extension from the flat plate shaped like a long "L".

The two rails are mounted on the aluminum base with four mounts. The small aluminum block runs on the rails connected by the two linear motion ball bearings. The bearing for rotation is pressed into a hole in the middle of the small aluminum block. The shaft is pressed into the center of the bearing for rotation and hangs down through a wide slit that is cut through the aluminum base and runs along the length of the base. The flat plate is clamped into a small slit cut into the shaft via screws and hangs below the base. There is an adjustable piece on the shaft and a small block that controls how far the flat plate can rotate (pitch/angle of attack). The maximum angle of attack can be set at an angle between 10 and 75 degrees from zero on either side. Maximum angle of attack was set at 40 degrees for all experiments in this report. The L-shaped moment arm is connected to the top of the flat plate and extends out forward from the flat plate.

Figure 3. The oscillating flow model.

III. TEST FACILITIES AND EXPERIMENTAL PROCEDURES

A. WATER TUNNEL ONE

1. Test Facility

Water Tunnel One is located in Halligan Hall, in the room adjacent to the Machine Shop. The test section is 27 inches high and 15 inches wide and is seen in Figure 4. The water level was set just below the metal ledges where the oscillator rested, so that the flat plate was fully submerged except for the very top portion where the moment arm was attached.

Figure 4. Water Tunnel One.

Water Tunnel One is equipped with a US Motors 15 hp centrifugal pump (52.1/49.3/24.65 V, 208/270/440 A, 60 Hz, 87-737 RPM), as shown in Figure 5. It uses a dial with settings from 0–3 to control the water speed. The dial setting were maintained less than 2.5 to avoid overworking the pump. The actual water speed corresponding to

settings of 1, 1.5, 2, and 2.5 were measured with a digital electromagnetic velocimeter. These water speeds are shown in Table 1. The meter automatically samples the water at 15 Hz and averages the water speed velocities into a 1 Hz output.

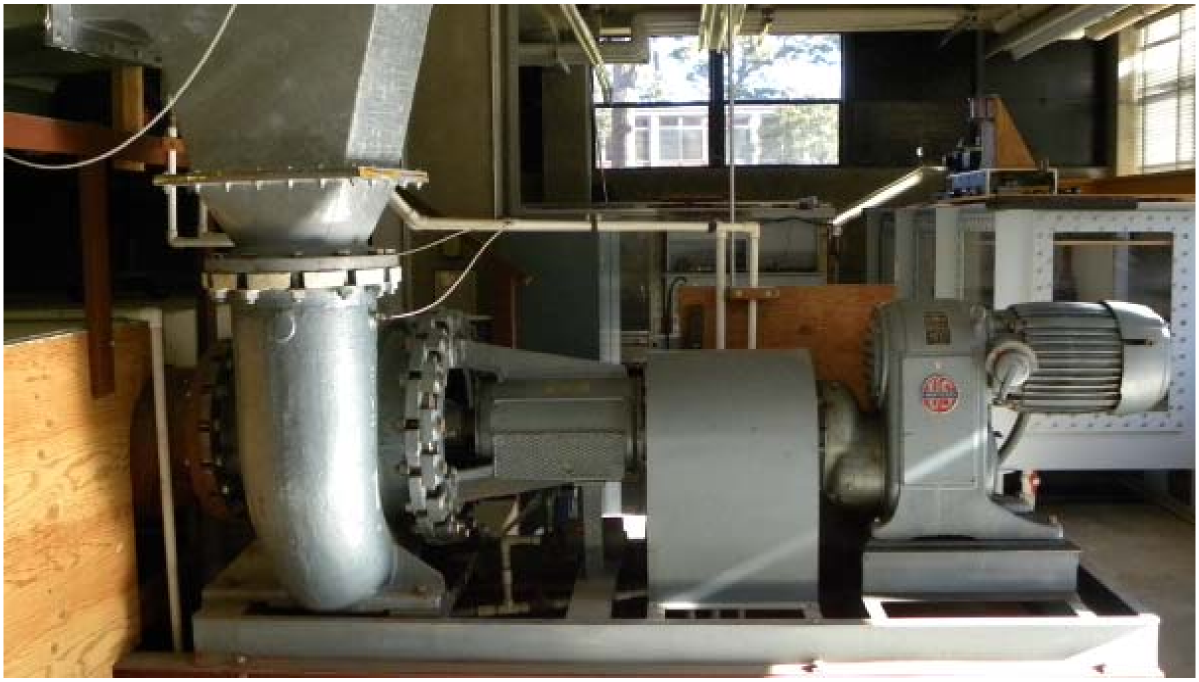

Figure 5. Water Tunnel One pump.

Evidently, the presence of a relatively dense screen at the downstream end of the test section (to prevent debris from being sucked into the pump) caused too much flow resistance for further speed increases. As the speed setting was increased, the flow in the test section was observed to become more and more wavy and non-uniform. When the screen was replaced by a courser screen, the water speed could be increased from 29 cm/s at a setting of 1 to 55 cm/s at a setting of 2.5, as shown in Table 1. However, the experimental results presented in this report were all obtained using the dense screen.

	Water Speed in cm/s	
Motor Setting	Fine Screen	Coarse Screen
1	29	29
1.5	35	35
2	34	46
2.5	34	55

Table 1. Water speeds measured for Water Tunnel 1.

2. Experiments

As explained in Section II, B, the oscillator consists of a flat plate that can be deflected to angles of attack ranging between 10 to 70 degrees. In these experiments, the maximum deflection angle was set at 40 degrees. Furthermore, the pitch axis location could be set at various distances from the plate leading edge. Selecting a pitch axis at or downstream from the mid-chord assures that the plate is statically unstable if placed in a flow. Hence, the plate deflects to an angle of plus or minus 40 degrees. If the plate was moved to the far left position and deflected to the right, a lift force was generated that caused the plate to move on the two rails to the right. The reversal of the plate motion was initiated as soon as the L-shaped moment arm touched the tunnel side wall (or the finger mounted on the oscillator in the towing tanks tests shown later). The plate kept moving to the right while the moment arm forced it to decrease the blade angle of attack (Figure 7) and eventually forced it into the zero angle of attack position (Figure 8) and to overshoot into a negative angle of attack position (Figure 9), which generated a leftward pointing lift force. In this way, blade motion reversal was accomplished by the fluid flow itself and the process repeated itself on the left side.

The oscillator was mounted into Water Tunnel One by resting the base on two metal rails running along the sides of the tank. The length of the oscillator was designed so that there was just enough clearance between the inner walls of the tank. The water level was filled to just below the base of the oscillator so that the flat plate was submerged with just the top above the waterline so that the moment arm was above the waterline.

The pump was started at an initial low dial setting of 1.1. At this point the small block moved to one side and sat still. At this low water speed, it was required to manually rotate the flat plate just past parallel to the flow to start it along on each traverse. Manual help was given on runs where the oscillator did not work on its own. This is noted in the description section of data analysis.

As the dial setting was increased, self-sustained blade oscillations were eventually achieved for certain water speeds and pitch axis locations, as documented in Tables 2, 3, and 4. Figures 6–10 show half of an oscillation. The blade approached the far wall at an angle of attack until the moment arm struck the wall. At that point, the small block continued toward the wall, slowed down, and the flat plate rotated to the neutral position (parallel to the water flow or zero degrees). The small block stayed at this position on the far wall until the flat plate was pushed past the neutral position to a slight angle of attack to the side opposite of when it approached the wall. The water flow forced the flat plate farther in this direction and the small block accelerated back toward the other side.

Figure 6. Flat plate travelling to the right at mid-deflection.

Figure 7. Oscillator moment arm contacting the wall.

Figure 8. Flat plate in the neutral position.

Figure 9. Flat plate beginning travel to the left.

Figure 10. Flat plate at full deflection traveling left and contacting the wall.

a. Experiment 1-1

For the first experiment, the short flat plate was used. Max angle of attack was set at 40 degrees for all experiments. The flat plate axis of rotation was adjusted to one of five locations: 5.1, 7.1, 9.0, 11.0 and 12.0 cm from the leading edge, corresponding to 36, 50, 63, 77, and 84 percent of chord. Each flat plate axis of rotation setting was tested four times for water speed dial settings of 1.1, 1.6, 2.1 and 2.3. We recorded approximately 1 minute of digital video for each scenario using a Cannon Powershot SD 970 digital camera. The camera recorded 30 frames per second. We determined the plate travel times and examined its behavior by studying the videos.

b. Experiment 1-2

For Experiment 1-2, the short flat plate was changed out for the long flat plate. This time, only three pitch axis locations were used: 7.0, 9.0 and 11.0 cm from the leading, corresponding to 49, 63, and 77 percent of chord. Each location was tested for the four different water speeds. A video recording was taken for each scenario in the same manner as in Experiment 1-1.

c. *Experiment 1-3*

For Experiment 1-3, the long flat plate was again used. This time two 2-ounce weights were added to the small block. The oscillator was again tested at pitch axis locations of 7.0, 9.0, and 11.0 cm from the leading edge at the four different water speeds and video recorded.

B. WATER TUNNEL TWO

1. Test Facility

Water Tunnel Two is located in the basement of Halligan Hall and shown in Figure 11. The water level is 45 cm high, with glass sides and an inner wall width of 38.2 cm.

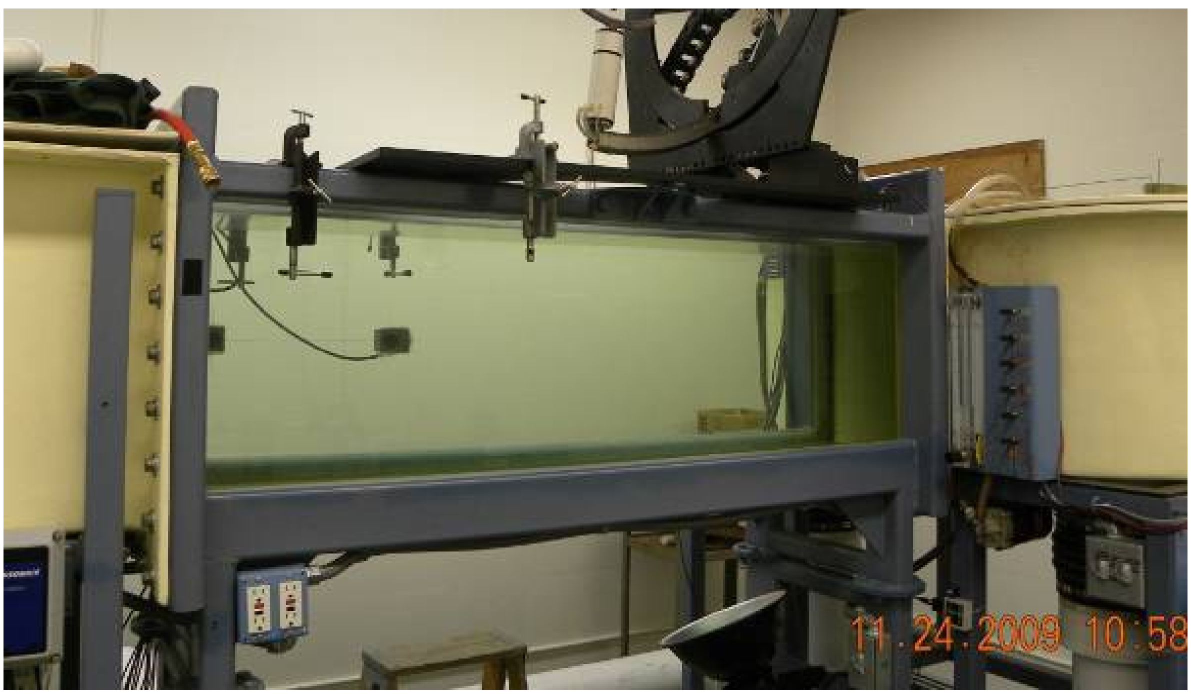

Figure 11. Water Tunnel Two.

Water Tunnel Two's pump (Figure 12) is a Brook Hanson high efficiency 5.0 hp centrifugal pump with the following ratings: 3 phase AC, s.f. 1.15, 230/460 V, 12.5/6.25 A, 1,740 RPM. The pump speed was controlled by entering operating frequencies into the control box. The pump operates at a safe frequency range of 0-40 Hz. According to

manufacturer supplied information, 0-40 Hz on the pump correlates to water speeds of 0-40 cm/s.

Figure 12. Water Tunnel Two pump.

2. Experiments

Water Tunnel Two operates at lower speeds than Water Tunnel One but has a more uniform flow. Experiments in this tank provided more consistent data because there were no noticeable effects caused by ripples and multidirectional flow streams.

The distance between the inner walls of Water Tunnel Two is slightly longer than the length of the aluminum base of the oscillator. Thin sheet metal was cut and shaped in such a manner to mount the oscillator down in between the tank walls and just above the water level. Magnets were used to help rotate the plate at the wall to change direction for the first three Tunnel Two experiments. One magnet was fixed at each wall and a coupled magnet was attached to the flat plate itself. As the plate approached the wall, the moment arm would begin to rotate the plate. To complete the rotation, the magnet on the wall opposed the magnet on the plate, and repelled it past the neutral (parallel to the water flow) position. See Figure 13.

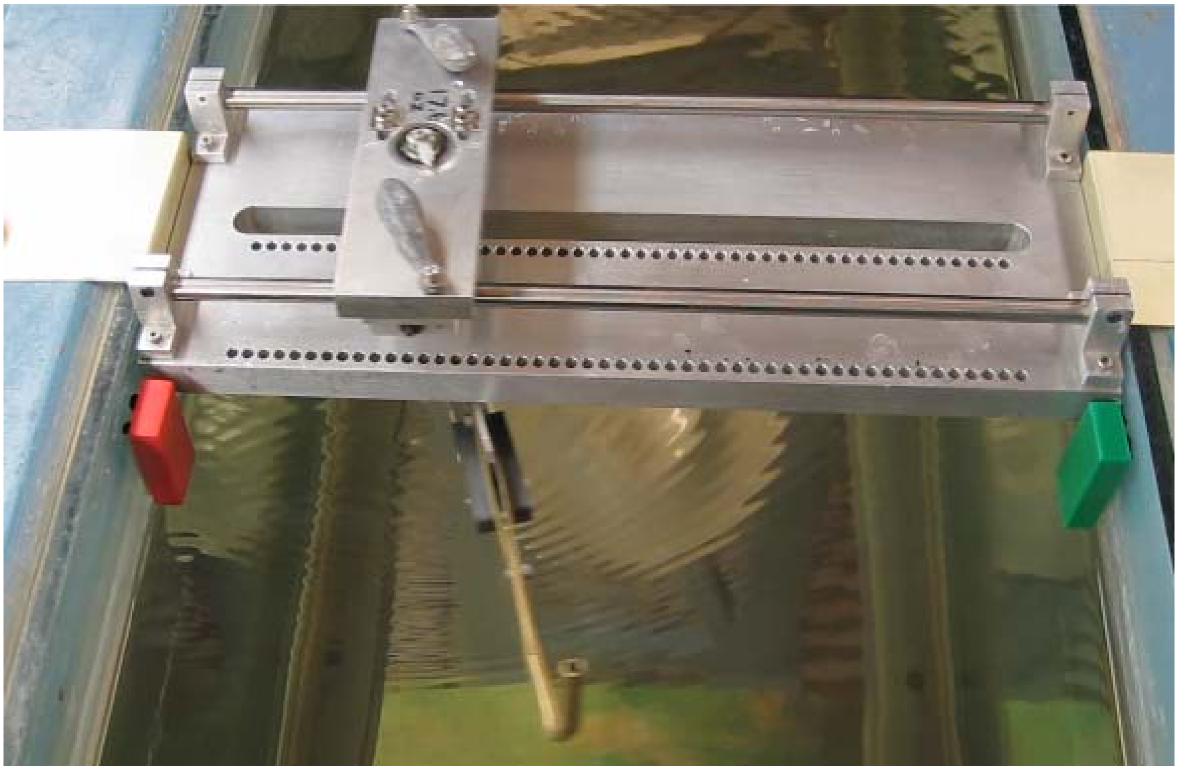

Figure 13. The oscillator with magnets for flat plate reversal and weights attached.

a. Experiment 2-1

Experiment 2-1 was conducted using the long flat plate on the oscillator. First, the pitch axis location was set at 10 cm from the leading edge. Runs were conducted at water speed settings of 20, 30 and 40 Hz. A video was recorded of each run lasting approximately 30 to 45 seconds. Runs were next completed for pitch axis locations of 11.5 and 8 cm from the leading edge at 20, 30 and 40 Hz.

b. Experiment 2-2

Experiment 2-2 was performed with the short flat plate. First, the pitch axis location was set to 10 cm from the leading edge. The flat plate did not oscillate on its own at 20 Hz. Runs were conducted at water speed settings of 25, 30 and 40 Hz and video recorded for analysis. For a pitch axis location of 12 cm from the leading edge, only the 40 Hz speed setting allowed the flat plate to oscillate on its own and this run was video recorded. Runs for speed settings of 25, 30 and 40 Hz were video recorded with

the pitch axis set at 8 cm from the leading edge. The purpose of this experiment was to contrast the performance of the long and short flat plates.

c. Experiment 2-3

Experiment 2-3 was performed with the short flat plate and two 2-oz weights (4 oz's total) attached to the small block. Runs were performed only for pitch axis location of 10 cm from the leading edge at 25, 30 and 40 Hz with video recordings for each. The purpose of this experiment was to test the effect of adding weight.

d. Flow Visualization

Colored dye was used to visualize the flow behavior as it passed by the flat plate during operation. Water Tunnel Two is equipped with dye injection. There are six dye containers that are pressurized with air from a compressor, as shown in Figure 14. The compressor works automatically, turning on when below a pressure set point and turning off when above a pressure set point. The dye is transported from the containers through a tygon tube where it can be released into the water tunnel through a small metal port that is connected to the end of the tube. Each dye container is of a different color and can be brought on or off line by a series of valve manipulations.

For flow visualization, the oscillator was set up in the water tunnel and for a series of different scenarios at a low water speed of 20 cm/s. For each scenario, the dye was released into the flow just upstream of the flat plate and at various distances off of the plate. For the first series of tests, the flat plate was held still at a number of angles of attack to see when the flow was attached and when it was separated. An illustration is shown in Figures 22–25 in the Data Analyis Section. Next, a turning motion was performed with the plate to visualize the flow effect as the plate rotated to change direction.

Figure 14. Dye injection containers in front of the air compressor.

Finally, the oscillator was set up in the water tunnel with magnets on the tunnel walls and on the flat plate as described in the Water Tunnel Two section earlier. A multiport dye injection piece was rigged on the flat plate via the moment arm and it was connected to the dye tubes. One side of the flat plate had dye released at the leading edge in two places; one within two millimeters of the plate and one two millimeters outside of the first. The water speed was maintained at 20 cm/s and the oscillator was observed in motion with the two dye streams released at the leading edge of the flat plate. See Figure 15.

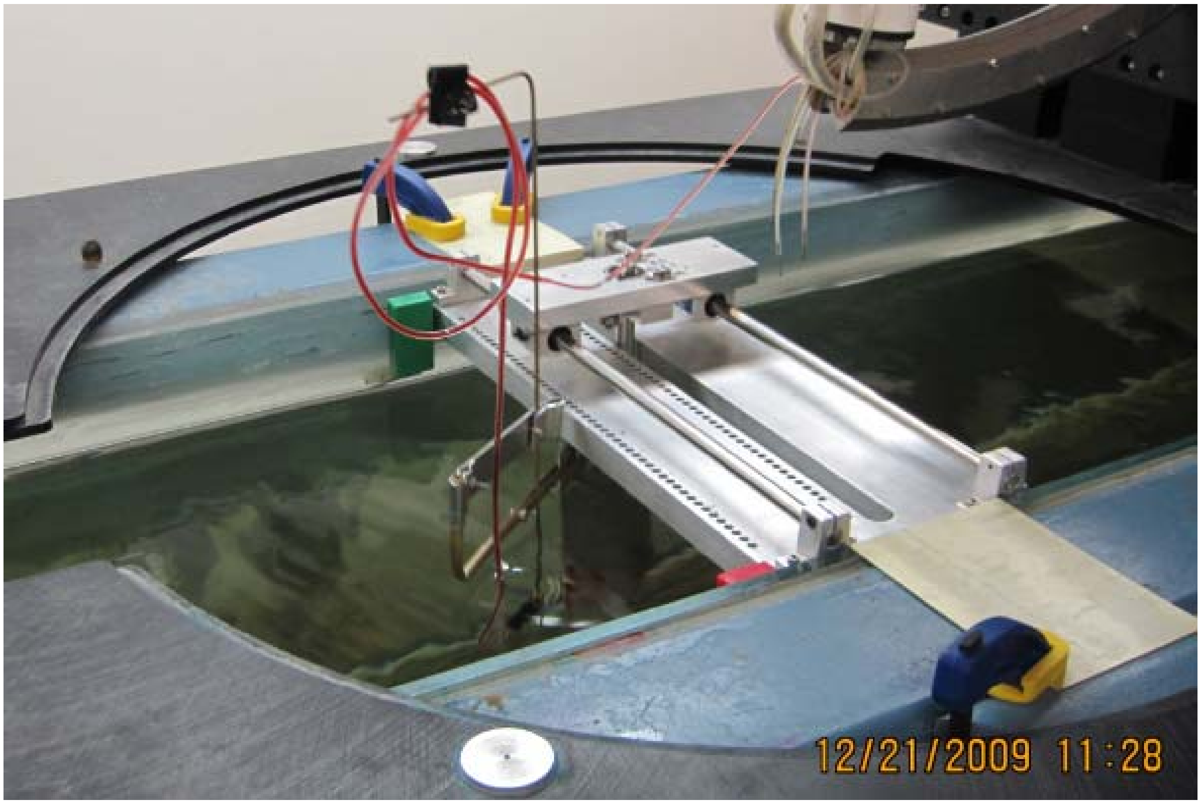

Figure 15. The oscillator set up in Water Tunnel Two with dye injection attached.

C. TOWING TANK

1. Test Facility

The Towing Tank is located next to Water Tunnel One in Halligan Hall adjacent to the Machine Shop and is shown in Figure 16. The Towing Tank is 32 feet long, 4 feet high and 3 feet wide. There is a set of 1-inch diameter rails located on the top of the tank walls that run down the length of the tank. A wooden shuttle is set up between the tank walls and connected to the rails by Thomson linear ball bearings and pillow blocks.

Figure 16. Side view of part of the Towing Tank.

2. Experiment

There is a pulley system that is used to move the shuttle down the track. A cable is attached to the shuttle that runs down the middle of the tank to a single pulley on the far side. The cable goes around the pulley and runs back down the entire length of the tank around a second pulley on the opposite side and runs back to the shuttle where it is attached to create a full circle. The second pulley is connected by an axle to a set of three pulleys encircled by a rubber belt. Rotating the belt around the pulleys moves the shuttle down track. See Figure 17.

Figure 17. Pulley system in the towing tank.

Two wooden 2x4's are extended down from the shuttle and connected to the oscillator so that the oscillator hangs down just above the waterline. Adjustments were made to ensure that the oscillator was situated level with the ground. Since the oscillator was not flush with the towing tank sidewalls, metal fingers were attached to either side of the aluminum base to contact the moment arm and facilitate blade reversal. The oscillator has the long flat plate attached with the pitch axis set 8.5 cm (60 % of chord) from the leading edge. The water level was set such that the lower 10.5 cm (35 %) of the blade was submerged. As with all experiments in this report, the angle of attack is limited to 40 degrees to either side. See Figure 18.

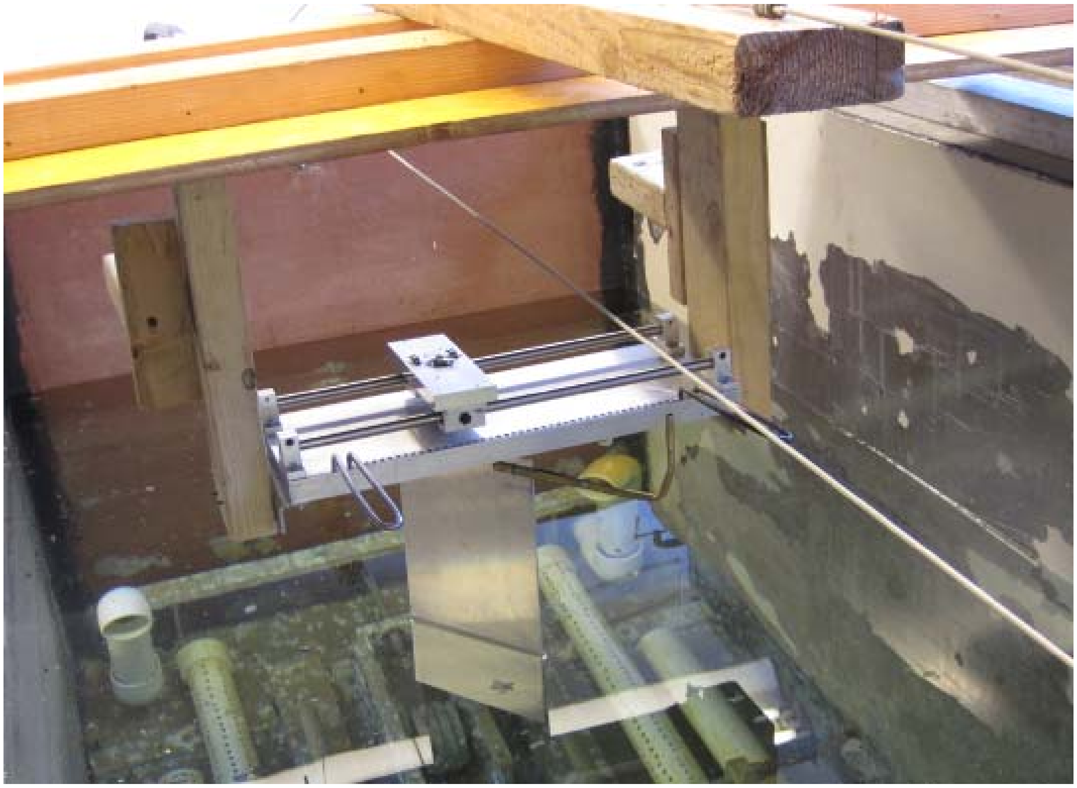

Figure 18. The Oscillator in the towing tank with the "fingers" attached.

The towing tank allowed for testing of the oscillator at higher relative water speeds than in Water Tunnels One and Two. The water in the tank is still so that the relative flow of water is smooth. Time was taken in between experiments to allow the waves created in the water to die down to an acceptable level for the next run.

There was no operational motor connected to the pulley system at the time of our experiments. The rubber belt encircling the three pulleys was pulled with a hand over hand technique to attempt a constant velocity. Inherently, velocity was not exactly constant, but we performed multiple runs and were able to successfully test the oscillator in the towing tank with higher water flow. Each run was video recorded. Tape was placed at intervals down the track to indicate distance traveled so we were able to figure out average velocity for the runs. Average velocity of the shuttle down the track correlates to water flow speed.

A 5 Hp motor will be connected to the pulley system for future experiments. With a motor, one will be able to achieve virtually constant velocity of the shuttle down the track.

D. VIDEO ANALYSIS

The video recordings were analyzed in Quick Time® software for all videoed experiments in Water Tunnels One and Two and in the Towing Tank runs. The video was recorded in 30 frames per second. For the first three experiments, the time it took the plate to travel from one side to the other was documented. With the oscillator's small block settled to one side, it was considered to have started a traverse when the plate (by watching the moment arm) began its rotation from neutral to an angle of attack. The frame number was recorded. When the small block settled (came to stop) at the other side, it was considered to have finished the traverse and the frame number was recorded. The difference of frame numbers from start to finish divided by thirty is the time in seconds for a traverse. For each run (water speed and pitch axis location), multiple times for traverse were recorded and then averaged. Only typical traverses were considered in the average. For instance, the time was not considered in the case where the oscillator got held up in the middle and began fluctuating back and forth before completing a full traverse. A qualitative description was assessed on each run taking notice of deflection (angle of attack) of the flat plate, consistency of the traverses, whether it was able to oscillate on its own, etc.

IV. DATA ANALYIS

A. WATER TUNNEL ONE EXPERIMENTS

The first three experimental data sets are summarized by the tables shown below. Average travel time is the average of several plate traverses. A traverse is considered to be the time that it takes the flat plate to go past neutral, starting the traverse from one side, until the traveling small block comes to rest on the other side. Average velocity is the distance traveled by the small block in a traverse divided by the average traverse time.

Each run was given a description. First, it was observed whether the oscillator works on its own and how consistently it worked. At lower speeds, each traverse was manually started by slowly turning the flat plate past neutral (using a finger on the moment arm) where the water flow took over and continued the rotation. At this point, lift was generated and the oscillator would complete a traverse. Consistency was represented by a general observation. Sometimes there was a wait time from one traverse to the other, the traverse got held up in the middle or the oscillator came back before completing a full traverse.

Next, it was observed whether the flat plate deflected during the traverse. A full deflection represented the highest angle of attack allowed by the limit set for the experiments at 40 degrees. Half deflection was halfway to that angle, 20 degrees, etc.

Finally the smoothness of travel was observed. At higher water speeds, the flow was not uniform one dimensional flow. That effect was seen as the plate travel was not a smooth traverse. It would cross in spurts of velocity, change directions and vary deflection angles.

1. Experiment 1-1

In Experiment 1-1, all runs completed with a speed setting of 1.1 required manual assistance for each traverse. In the runs with a pitch axis location of 9 cm from the leading edge, the oscillator worked inconsistently and the flat plate deflection reached half of maximum. The 11 cm pitch axis location worked inconsistently except at the

highest speed setting of 2.3, where it was consistent. The flat plate fully deflected at the lower two water speed setting and deflected half for the higher settings. The 12 cm pitch axis location worked consistently for all water speed settings except for 1.1. The plate deflected fully for the lower speed settings and halfway for higher speed settings. The 7 cm pitch axis location was inconsistent with half deflection for speed setting 1.6 and did not work well at all at higher speed settings. Pitch axis location 5.1 cm did not work on its own. See Table 2 for a full description of each run.

Run	Water Speed Setting	Pitch Axis Location (cm)	Average Travel Time (s)	Average Velocity (cm/s)	Description
1	1.1	9.00	4.14	8.70	Needs manual assistance. Full deflection. Travel smooth.
2	1.6	9.00	2.54	14.17	Works on its own inconsistently. Half deflection. Travel not smooth.
3	2.1	9.00	2.78	12.95	Works on its own inconsistently. Half deflection. Travel not smooth.
4	1.1	11.00	3.51	10.26	Needs manual assistance. Full deflection. Travel smooth.
5	1.6	11.00	2.68	13.43	Works on its own inconsistently. Full deflection. Smooth travel.
6	2.1	11.00	2.96	12.16	Works on its own inconsistently. Half defection. Smooth travel.
7	2.3	11.00	2.61	13.79	Works on its own consistently. Half deflection. Travel not smooth.
8	1.1	12.00	3.74	9.63	Needs manual assistance. Full deflection. Travel smooth.
9	1.6	12.00	2.77	13.00	Works on its own consistently. Full deflection. Travel smooth.
10	2.1	12.00	2.83	12.72	Works on its own consistently. Half deflection. Travel not smooth.
11	2.3	12.00	2.72	13.24	Works on its own consistently. Half deflection. Travel not smooth.
12	1.1	7.10	5.10	7.06	Needs manual assistance. Quarter deflection. Travel not smooth.
13	1.6	7.10	2.83	12.72	Works on its own inconsistently. Half deflection. Travel not smooth.
14	2.1	7.10	n/a	n/a	Too inconsistent for analysis.
15	2.3	7.10	n/a	n/a	Too inconsistent for analysis.
16	1.1	5.10	n/a	n/a	Too inconsistent for analysis.
17	1.6	5.10	n/a	n/a	Too inconsistent for analysis.
18	2.1	5.10	n/a	n/a	Too inconsistent for analysis.
19	2.3	5.10	n/a	n/a	Too inconsistent for analysis.

Table 2. Data from Experiment 1-1.

2. Experiment 1-2

Again all runs completed with a 1.1 speed setting needed manual assistance. The 9 cm pitch axis location run worked consistently well and at half deflection at the 1.6 speed setting. Speed settings of 2.1 and 2.3 were at quarter deflection and worked inconsistently. Pitch axis location at 11 cm worked consistently well with half deflection for all speed settings above 1.1. A pitch axis of 7 cm did not work consistently for any speed setting. The Experiment 1-2 data table is shown in Table 3.

Table 3.

Run	Water Speed Setting	Pitch Axis Location	Average Travel Time	Average Velocity (cm/s)	Description
1	1.1	9.00	4.12	8.74	Needs manual assistance. Half deflection. Travel smooth.
2	1.6	9.00	3.26	11.04	Works on its own consistently. Half deflection. Travel not smooth.
3	2.1	9.00	n/a	n/a	Works on its own inconsistently. Quarter deflection. Travel not smooth.
4	2.3	9.00	n/a	n/a	Works on its own inconsistently. Quarter deflection. Travel not smooth.
5	1.1	11.00	4.40	8.18	Needs manual assistance. Half deflection. Travel smooth.
6	1.6	11.00	3.58	10.06	Works on its own consistently. Half deflection. Travel smooth.
7	2.1	11.00	3.67	9.81	Works on its own consistently. Half deflection. Travel not smooth.
8	2.3	11.00	3.83	9.40	Works on its own consistently. Half deflection. Travel not smooth.
9	1.1	7.00	5.99	6.01	Needs manual assistance. Quarter deflection. Travel smooth.
10	1.6	7.00	n/a	n/a	Too inconsistent for analysis.
11	2.1	7.00	n/a	n/a	Too inconsistent for analysis.
12	2.3	7.00	n/a	n/a	Too inconsistent for analysis.

Table 4. Data from Experiment 1-2.

3. Experiment 1-3

All runs completed with a 1.1 speed setting needed manual assistance. The 7 cm pitch axis location did not work on its own consistently for any speed setting. The 11 cm pitch axis worked on its own (but inconsistently) and with half deflection angle for all speed settings above 1.1. The 9 cm pitch axis was inconsistent with quarter deflection for speed setting 1.6 and inconsistent with half deflection for 2.1 and 2.3. See Table 4 .

Run	Water Speed Setting	Pitch Axis Location	Average Travel Time	Average Velocity (cm/s)	Description
1	1.1	7.00	5.15	6.99	Needs manual assistance. Half deflection. Travel smooth.
2	1.6	7.00	n/a	n/a	Too inconsistent for analysis.
3	2.1	7.00	n/a	n/a	Too inconsistent for analysis.
4	2.3	7.00	n/a	n/a	Too inconsistent for analysis.
5	1.1	11.00	3.94	9.14	Needs manual assistance. Half deflection. Travel smooth.
6	1.6	11.00	3.55	10.14	Works on its own inconsistently. Half deflection. Travel smooth.
7	2.1	11.00	3.27	11.01	Works on its own inconsistently. Half deflection. Travel not smooth.
8	2.3	11.00	3.16	11.39	Works on its own inconsistently. Half deflection. Travel not smooth.
9	1.1	9.00	4.88	7.38	Needs manual assistance. Half deflection. Travel smooth.
10	1.6	9.00	3.79	9.50	Works on its own inconsistently. Half deflection. Travel not smooth.
11	2.1	9.00	n/a	n/a	Works on its own inconsistently. Quarter deflection. Travel not smooth.
12	2.3	9.00	n/a	n/a	Works on its own inconsistently. Quarter deflection. Travel not smooth.

Table 5. Data from Experiment 1-3.

B. WATER TUNNEL TWO EXPERIMENTS

The second set of experimental data (Experiments 2-1 through 2-3) is summarized in Tables 5 through 7. For this set, the tests took place in Water Tunnel Two. The description column merely describes the flat plate deflection behavior for the traverses of each run. Runs 6 and 7 in Table 6 have an extra note in the description. The oscillator paused for a few seconds on its way across only when going from left to right.

1. Experiment 2-1

Run	Water Speed (cm/s)	Pitch Axis Location (cm)	Average Travel Time (s)	Average Velocity (cm/s)	Description
1	20.00	10.00	4.80	7.50	Full deflection
2	30.00	10.00	4.16	8.65	Near full deflection
3	40.00	10.00	4.21	8.55	Half deflection
4	20.00	11.50	4.88	7.38	Full deflection
5	30.00	11.50	3.77	9.55	Near full deflection
6	40.00	11.50	3.18	11.32	Half / Near full deflection
7	20.00	8.00	5.15	6.99	Half / Near full deflection
8	30.00	8.00	5.11	7.05	Quarter / Half deflection
9	40.00	8.00	5.31	6.78	Minimum deflection

Table 6. Data from Experiment 2-1.

2. Experiment 2-2

Run	Water Speed (cm/s)	Pitch Axis Location (cm)	Average Travel Time (s)	Average Velocity (cm/s)	Description
1	20.00	10.00	3.50	10.29	Full deflection
2	30.00	10.00	3.27	11.01	Full deflection
3	40.00	10.00	2.81	12.81	Near full deflection
4	40.00	11.50	2.41	14.94	Full deflection
5	25.00	8.00	3.67	9.81	Near full deflection
6	30.00	8.00	3.06	11.76	Half deflection. Stalls when crossing from left to right every time.
7	40.00	8.00	2.81	12.81	Quarter deflection. Stalls when crossing from left to right every time.

Table 7. Data from Experiment 2-2.

3. Experiment 2-3

Run	Water Speed (cm/s)	Pitch Axis Location (cm)	Average Travel Time (s)	Average Velocity (cm/s)	Description
1	20.00	10.00	3.31	10.88	Full deflection
2	30.00	10.00	3.14	11.46	Full deflection
3	40.00	10.00	3.04	11.84	Near full deflection

Table 8. Data from Experiment 2-3.

4. Graphs

Results for different parameters were analyzed by constructing three graphs out of the data from Tables 5 through 7. Each graph plots the flat plate's average velocity on the y-axis versus water flow velocity on the x-axis. Figure 19 displays data from the tests for three pitch axis locations recorded in Experiment 2-1 with the long flat plate. Figure 20 compares the data at the 10 cm pitch axis location from Experiment 2-1 (long flat

plate) with that of Experiment 2-2 which uses the short flat plate. Figure 21 shows the data from Experiment 2-1 (short plate without weights added) versus that of Experiment 3-1 (short plate with weights added). Figure 21 data sets had a 10 cm pitch axis location.

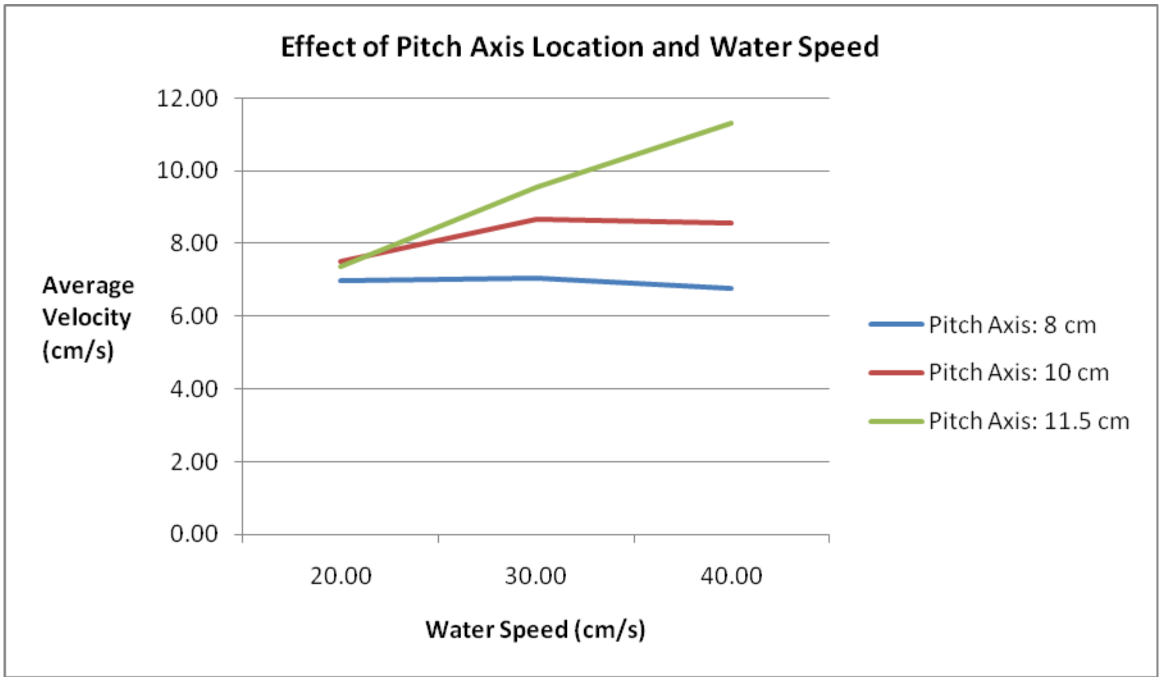

Figure 19. Graph of average velocity versus water speed for three different pitch axes.

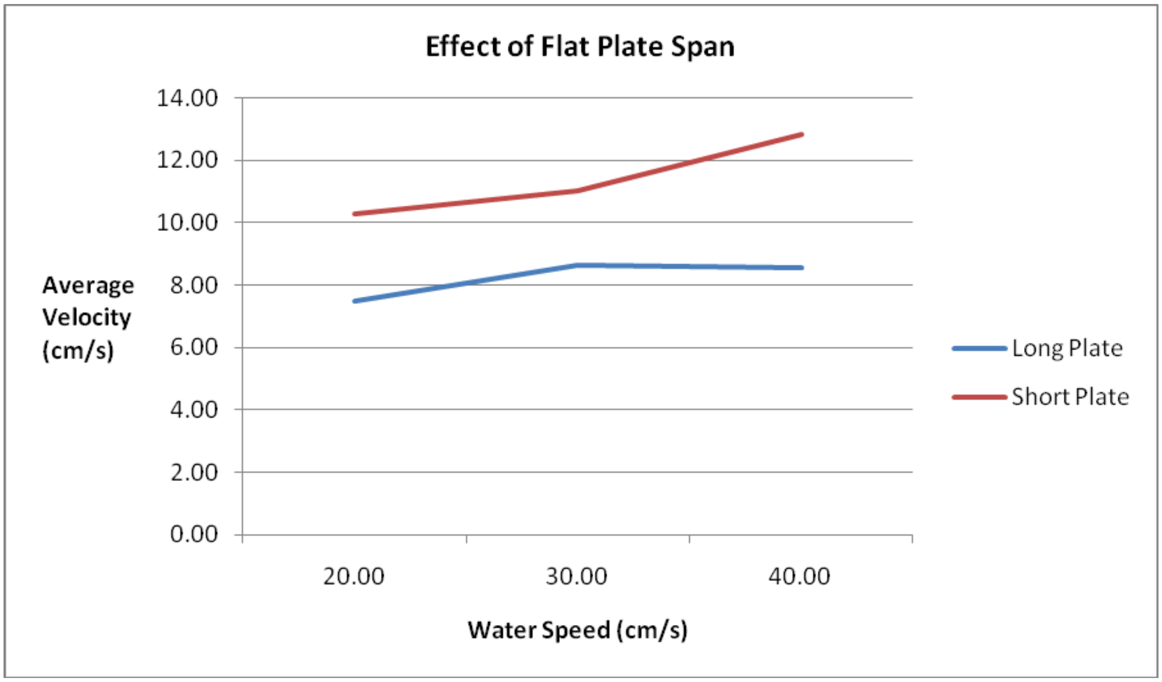

Figure 20. Average plate velocity of oscillator versus water speed for two plate sizes.

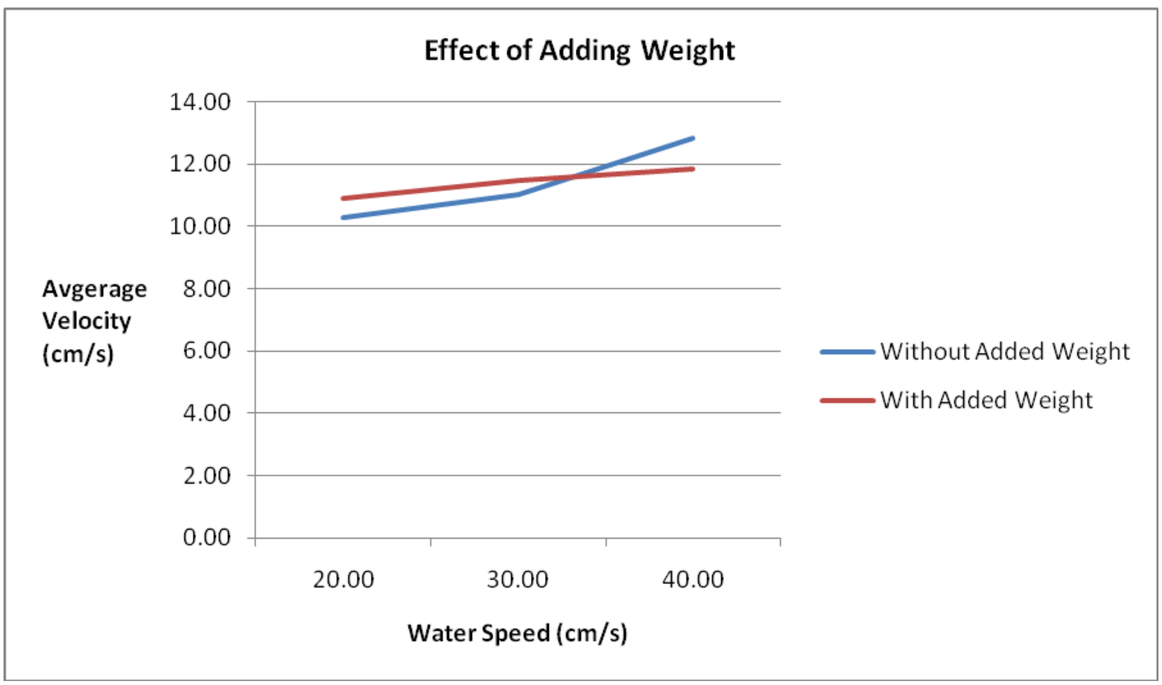

Figure 21. Average plate velocity versus water speed with and without added weight.

5. Flow Visualization

Dye flow visualizations are shown in Figures 22–25. Figure 22 shows the pressure side at a small angle of attack. Figure 23 is the suction side at a very slight angle of attack (almost neutral). Figures 24 and 25 are the suction side of the plate at a few degrees higher angle of attack successively.

Figure 22. Attached laminar dye stream.

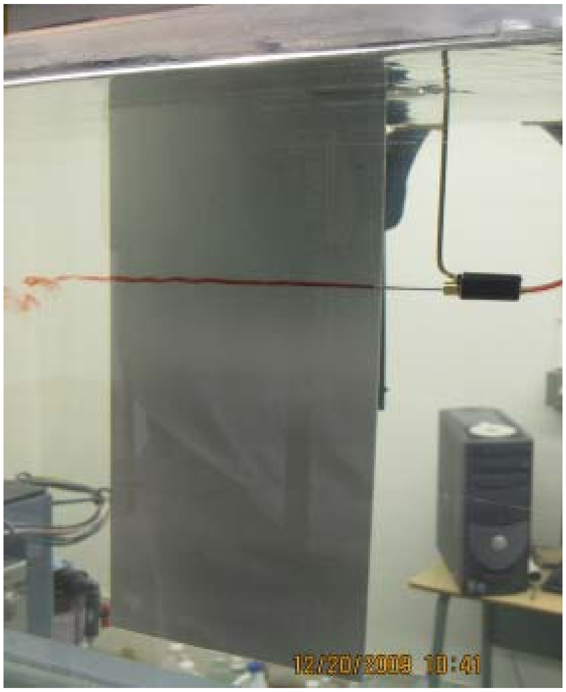

Figure 23. Attached transition to turbulent dye stream.

Figure 24. Initial flow separation of dye stream.

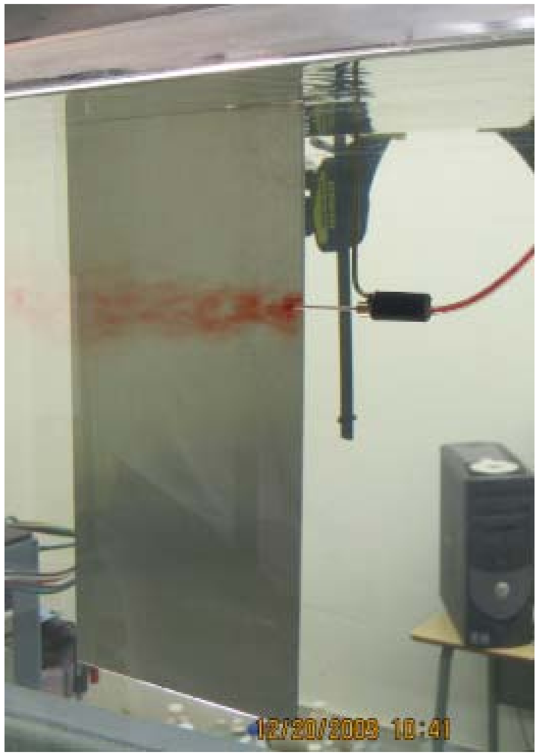

Figure 25. Flow separation of dye stream.

C. TOWING TANK EXPERIMENTS

Figures 26–30 show the oscillator near the end of the track of the towing tank in Run 1 of the Towing Tank Experiments. The figures show just over half of an oscillation. Each picture is labeled with a frame number from the recorded video to indicate time passed (30 frames per second). In each successive figure, the wooden shuttle is further down track and the oscillator has traversed further along the rails. The oscillator moment arm struck the attachable metal fingers on either side of the aluminum base and not the towing tank walls. The figures show the oscillator approach one side, reverse the angle of attack and continue back to the original location at the reversed angle of attack.

Figure 26. Towing Tank Run 1 Frame 364.

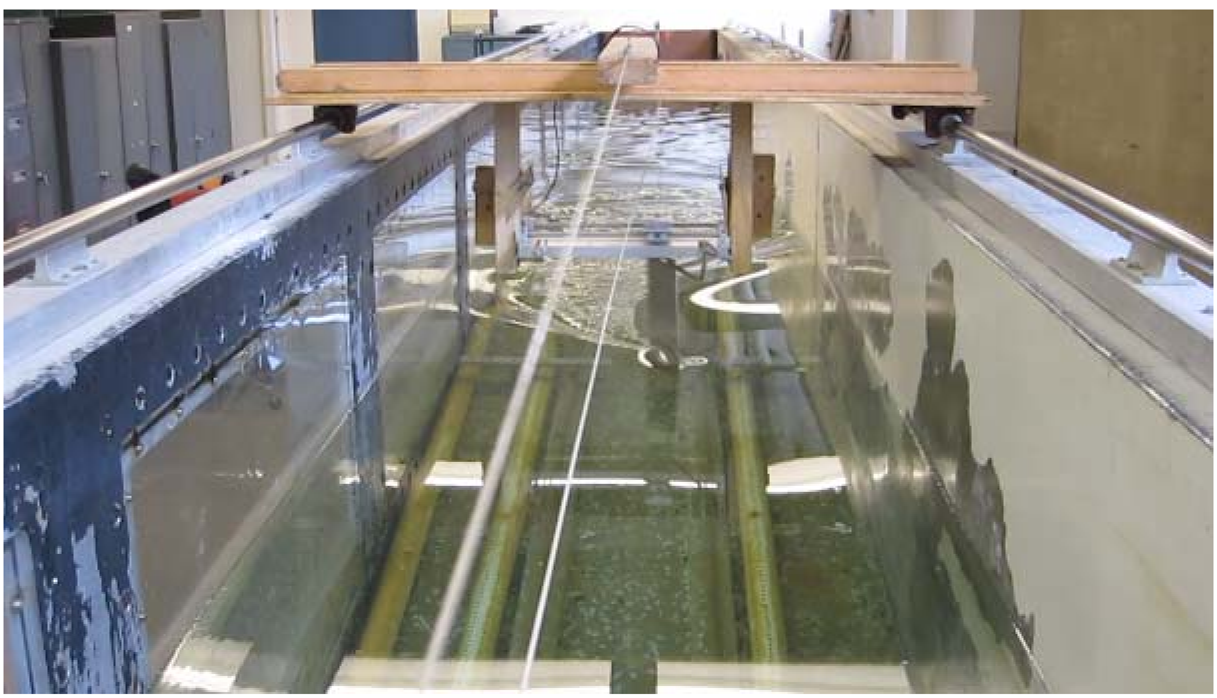

Figure 27. Towing Tank Run 1 Frame 369.

Figure 28. Towing Tank Run 1 Frame 374.

Figure 29. Towing Tank Run 1 Frame 382.

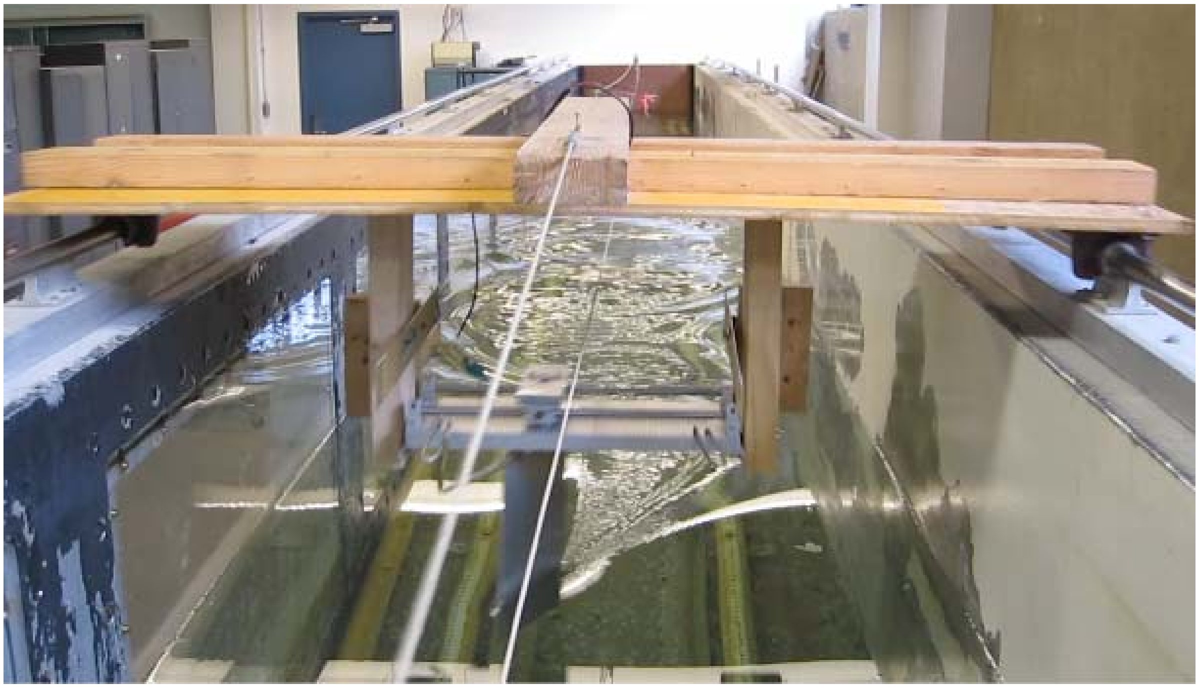

Figure 30. Towing Tank Run 1 Frame 392.

Video of three towing tank runs were analyzed and data was compiled as shown in Table 8. The distance traveled by the shuttle down track and the time it took to do so are shown in columns 2 and 3. Run 1 was completed on a different day and the video was recorded from a different perspective (showing more track length) than the other two runs. Relative water speed is simply distance traveled by the shuttle divided by time of travel. The number of oscillations completed by the plate was counted for each run. One oscillation was completed when the small block traveled two track lengths. The frequency is oscillations per second.

Run	Distance (m)	Time (s)	Relative Water Speed (cm/s)	Number of Oscillations	Frequency (Hz)
1	8.53	6.83	125	4.5	0.66
2	6.1	4.53	135	3	0.66
3	6.1	6.03	101	4	0.66

Table 9. Towing Tank Test Data.

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V. DISCUSSION

A. TEST FACILITY CONDITIONS

The experiments show that it is possible to induce a flat plate into self-sustained linear oscillation, provided certain geometric and flow conditions are met.

In Water Tunnel One, the flat plate was subjected to water flow with ripples and noticeable imperfections. During runs at speeds at 1.6 and lower, the flow was relatively uniform but the oscillator did not work on its own. Manual assistance was required to achieve blade reversal at each side. In runs at speeds higher than the 1.6 setting and with sufficiently far downstream pitch axis locations, the flat plate was able to reverse on its own. The plate would approach the flat wall at one side of the tunnel and the moment arm would strike the wall. The moment arm was able to bring the flat plate from an angle of attack to the neutral position flush with the wall and parallel to the flow as seen in Figure 8. Because of the slightly multidirectional flow, the flat plate would eventually bump from a neutral angle of attack to a slight angle in the reverse direction. At this point, the lift force on the flat plate at a slight angle of attack continued to rotate the flat plate to a larger angle of attack and the plate began its traverse to the other side. The time it took for the plate to go from the neutral position to the start of the next traverse varied from milliseconds to numerous seconds. The non-uniform flow also created inconsistent behavior during each traverse. At some pitch axis/flow speed combinations the plate would inch its way across in spurts. Sometimes it would go half way across and reverse back without making it to the other wall. Deflection angle sometimes varied for each traverse on the same run.

Water Tunnel Two provided uniform one-dimensional flow. The plate traversed with nice “smooth” strokes in this flow, which made it possible to gain relatively consistent data for a given set of experimental conditions. Blade reversal did not work like it did in Water Tunnel One with just a flat wall. After the moment arm brought the flat plate to the neutral position, there were no flow imperfections to bump it to a slight angle of attack. Magnets were used to help with blade reversal. Magnets placed at each

wall opposed magnets placed on the top forward position of the oscillator flat plate. As the plate approached the wall, the moment arm started the blade reversal, and as the flat plate got closer to the wall, the magnetic field force contributed to get the flat plate past neutral. The oscillator worked on a consistent basis at different pitch axis locations, water speeds, flat plate span and with weight addition.

The towing tank provided uniform flow at relative fluid flow speeds approximately three times greater than the water tunnels. In the case of the towing tank, the momentum gained by the oscillator small block was great enough to allow for blade reversal with uniform flow and without magnets. Attachable metal fingers on the ends of the aluminum base consistently pushed the moment arm past the neutral position for blade reversal. The traverses were very smooth. Optimum performance was achieved in the towing tank.

B. PITCH AXIS LOCATION

Pitch axis location affects how much moment is created by the flow to rotate the blade. The lift force acts near mid-chord of the flat plate (7.15 cm from the leading edge). Therefore, if the pitch axis is located at mid-chord, then the flow will not impart a moment to rotate the flat plate. If the pitch axis is located forward of mid-chord (toward the leading edge), then the flat plate will remain in the neutral position much like a weather vane that points in the direction of wind flow. Table 2 shows that the oscillator did not work for pitch axis locations of 7.1 and 5.1 cm from the leading edge.

The moment arm that the lift force used to rotate the flat plate is equal to the distance of the pitch axis from mid-chord. For example, there is an approximate 2 cm moment arm for a pitch axis located 9 cm from the leading edge. Figure 19 shows that the further back the pitch axis location, the higher the average velocity of the flat plate. The descriptions in Table 5 indicate that this is because pitch axis locations further back allow larger angles of attack during the traverses. Larger angles of attack correlate to more lift and hence more power generation. This indicates that a pitch axis location at the trailing edge would be ideal. There is a tradeoff, however. In experiments in Water Tunnel 2, pitch axis locations further back than 11.5 cm would not reverse at the wall.

The moment created by the fluid flow was too great to be overcome by the moment gained by the moment arm striking the wall and magnetic field force. A pitch axis location of 11.5 cm was ideal for oscillator performance in Water Tunnel Two since it allowed the oscillator to work on its own and maximize the power generation potential.

C. FLAT PLATE SPAN

Figure 20 indicates that the shorter flat plate span traversed at a higher average velocity than the longer flat plate. One would think that a longer span would create more force in the transverse direction for higher average flat plate velocity and more possible power generation. Other factors negated this. A longer span can also created more drag in the direction of flow, which created reaction forces on the linear bearing and rail interface. There was more moment on the flat plate from fluid flow which translated to reaction forces on the linear bearing and rail interface when the flat plate is at full deflection. Drag in the traversing direction may also play a role in slowing down the plate with longer plate span. Future experimentation and analysis is required to determine optimum flat plate span.

D. ADDED WEIGHT

Figure 21 does not conclusively show that adding weight to the small block of the oscillator lowers the average velocity. When performing experiment 2-3, the oscillator worked consistently only for the 10 cm pitch axis location. Experiment 1-2 had more consistent performance than experiment 1-3 did with weights added. This indicates that the added load did indeed hamper oscillator performance. The purpose of adding the weight was to simulate adding a load for power generation.

E. WATER SPEED

Figures 15–17 most closely demonstrate a linear increase in average flat plate traversing velocity with an increase in fluid flow speed for Water Tunnel Two experiments. It is evident that higher fluid flow allows for higher power extraction since higher fluid flow for the same angle of attack and flow conditions yields more lift. The

oscillator performed extremely well in the towing tank where relative fluid flow speed was at a maximum.

As fluid flow was increased in Water Tunnel One, the oscillator more easily achieved flat plate reversal. However, at higher water speeds, deflection angle did not reach full deflection and flow imperfections were greater and caused performance inconsistency. Average traverse velocity was still greater for higher water speeds.

VI. CONCLUSIONS

1) The oscillating flow generator successfully oscillated a flat plate on its own under a variety of experimental conditions in all three test facilities. It was shown that blade reversal could be induced by the fluid flow itself, without a mechanical or electromechanical control system. Each facility was unique. Water Tunnel One had non-uniform flow that allowed oscillator blade reversal for most conditions using only the moment arm on the side walls. Water Tunnel Two provided uniform flow that yielded consistent oscillator performance but demanded magnets to assist in flat plate reversal. The Towing Tank proved that the oscillator worked well in high relative fluid flow velocity.

2) Parameters that had the most influence on oscillator performance were pitch axis location, flat plate span length, fluid flow velocity, and deflection angle. Peak performance occurred with the pitch axis located between 60-70 percent chord with maximum fluid flow velocity.

3) Flow visualization verified that flow separation occurs while the flat plate is at an angle of attack. This was unavoidable as large angles of attack were necessary to obtain a sufficient lifting force for power generation capability.

Further study of the oscillating flow generator is recommended to determine the conditions necessary to maximize performance and to fully understand the physical nature of this device.

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